Development of a Gossamer Photovoltaic Sail

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There are no basic physical principles that would prevent the development of extremely thin, yet efficient, photovoltaic materials deposited on a flexible, plastic film. In this paper, a sail of this type with a mass-to-area ratio of 20 gram/sqm is postulated. The sail, of rectangular shape, has no rigid structural elements, but is stabilized by thrust vector control of ion engines at each corner. In addition to providing for the vehicle's thrust and for orienting and stabilizing the sail, these engines are also used to aid the deployment of the sail from an initial rolled up configuration. The voltage is constant, but the ion mass flow rate is controlled to vary proportional to the solar input, i.e. indirectly proportional to the square of the distance from the sun. A space mission is described in which a vehicle, starting from LEO, would acquire a velocity of escape from solar gravity far greater than what can be achieved by multiple planetary fly-bys. In just five years of flight, the distance from the sun could be 200 AU. (By comparison, Pioneer 10, launched nearly 30 years ago, is now "only" at 76 AU). A much higher ultimate velocity yet might be achieved by a solar fly-by at 0.3 AU from the sun. This paper is an extension of a paper, recently published: Rudolf X. Meyer, "Solar-Electric Ion Propulsion: Future Possibilities", Jr. of the Astronautical Sciences, Vol.47, pp.47-52, 1999.

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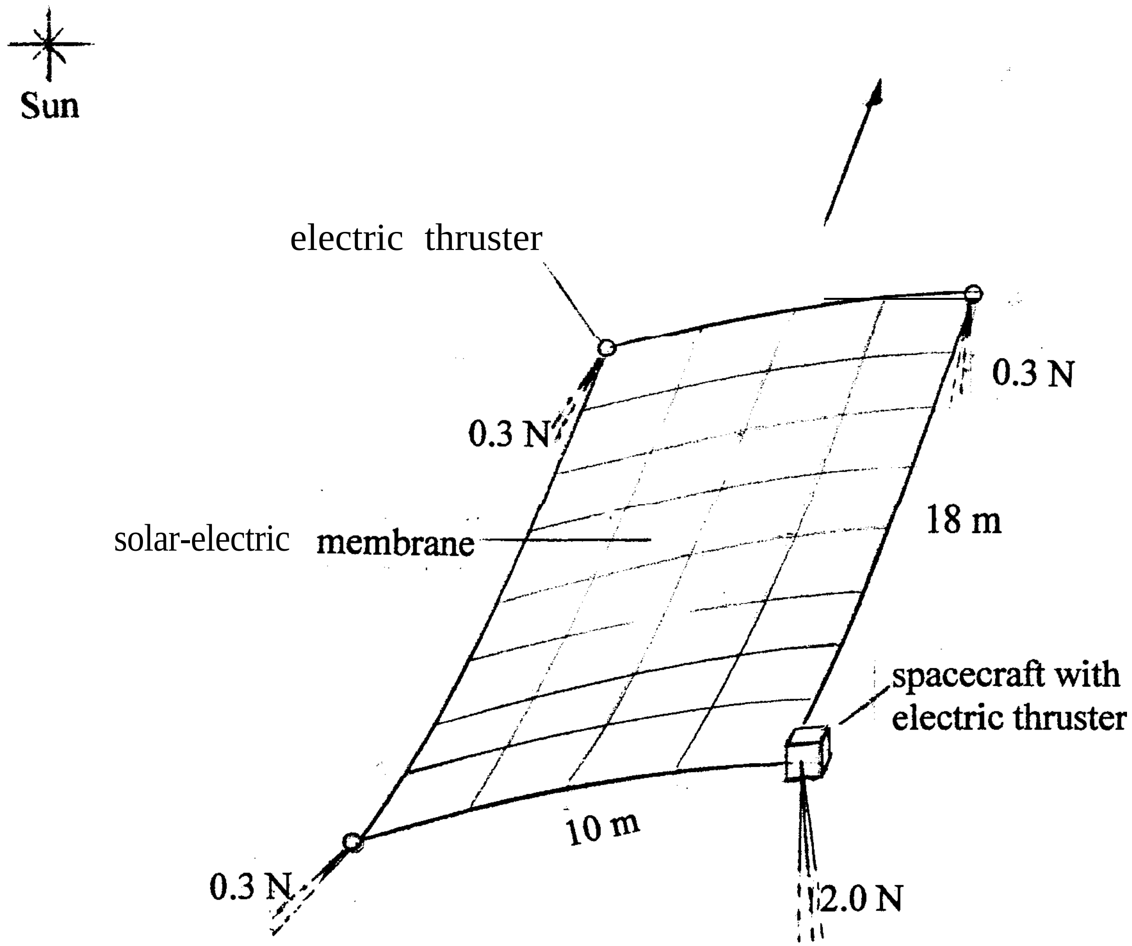
The "Flying Carpet" Concept



Rudolf X. Meyer
Thursday, 1:20 pm

initial mass = 625 kg
final mass = 125 kg

Incident solar power: $$P_h(r) = A_e J_0 \frac{r_0^2}{r^2}$$

where J_0 = solar constant = 1360 W/m^2

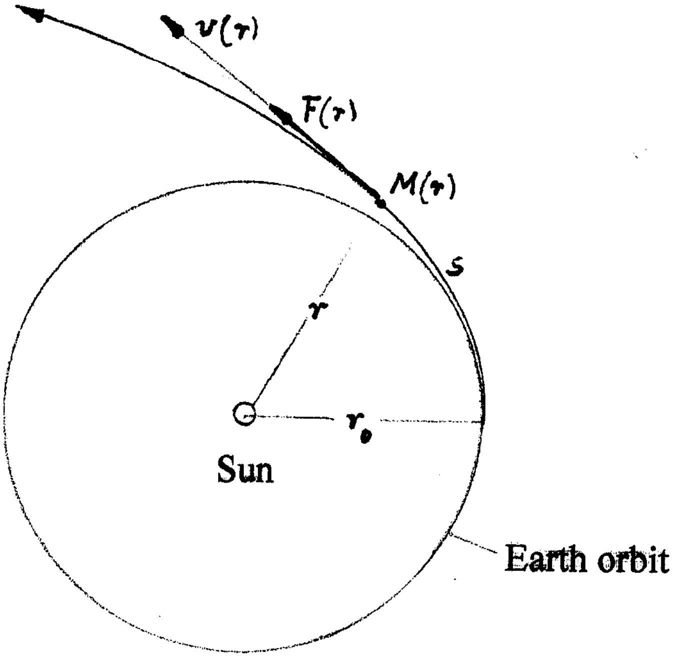
Ion beam power: $$P_i(r) = \eta_e \eta_i P_h(r) = \frac{1}{2} \tilde{m}_i(r) u_i^2 = -\frac{1}{2} \frac{dM}{dt} u_i^2 = $$
$$= \frac{1}{2} u_i^2 v(r) \left(-\frac{dM}{ds} \right)$$

where u_i = ion beam velocity relative to vehicle = const.

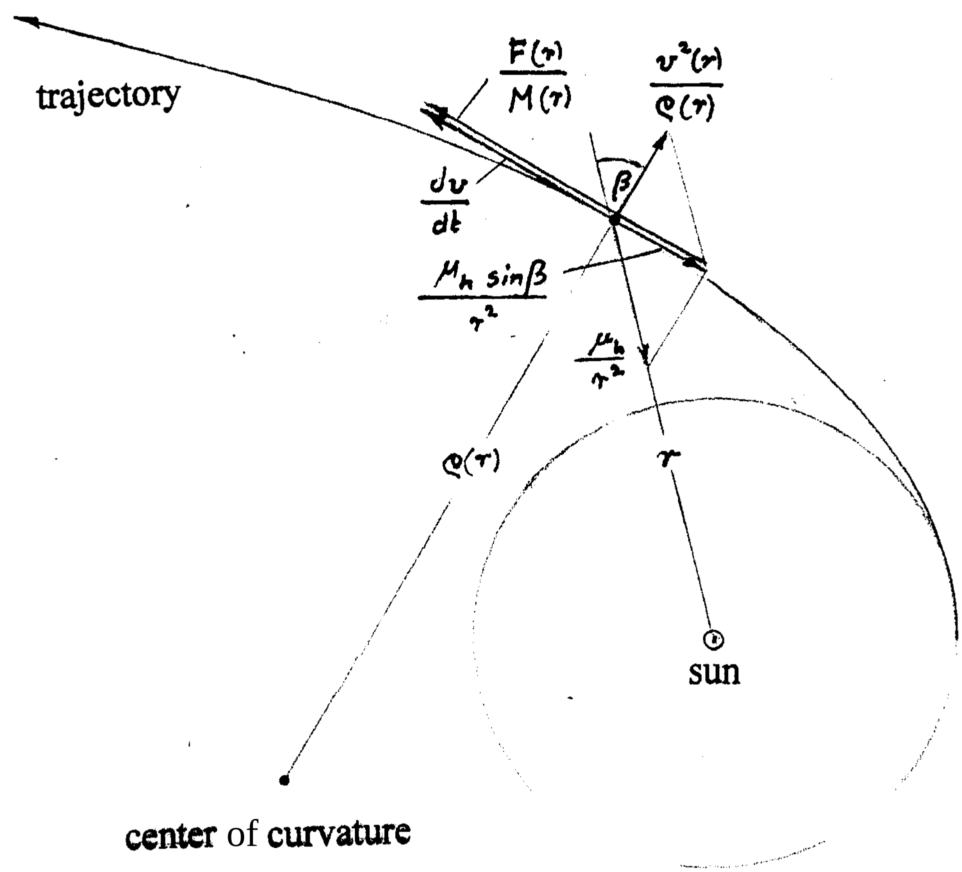
Accel. potential: $$eV_i = \frac{1}{2} m_x u_i^2 = const.$$

Current: $$I_i(r) = \frac{P_i(r)}{V_i} = \frac{\eta_e \eta_i A_e J_0 \left(\frac{r_0}{r} \right)^2}{V_i}$$

Thrust: $$F(r) = \tilde{m}_i(r) u_i = \frac{2 P_i(r)}{u_i}$$



The Flying Carpet Concept

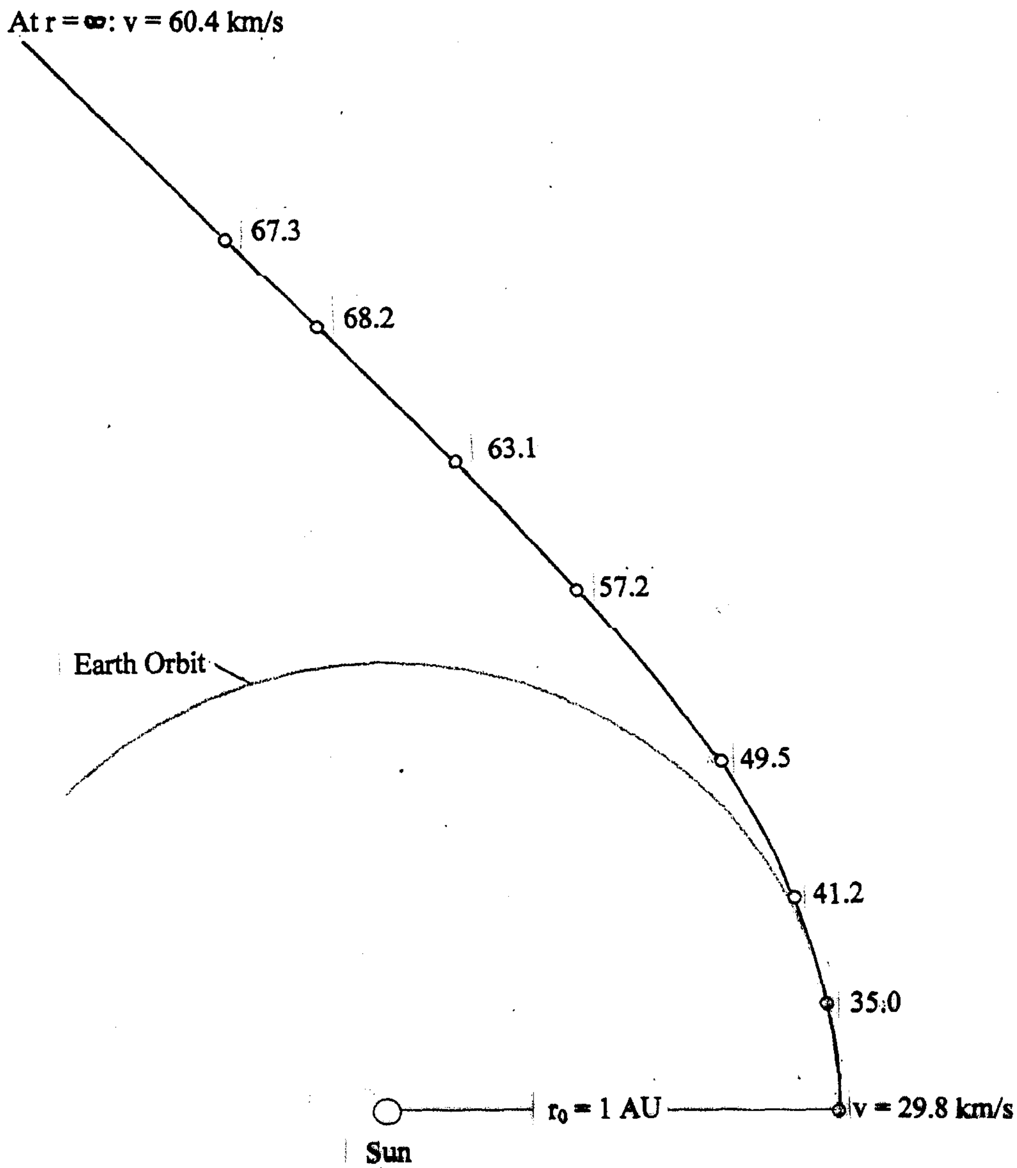


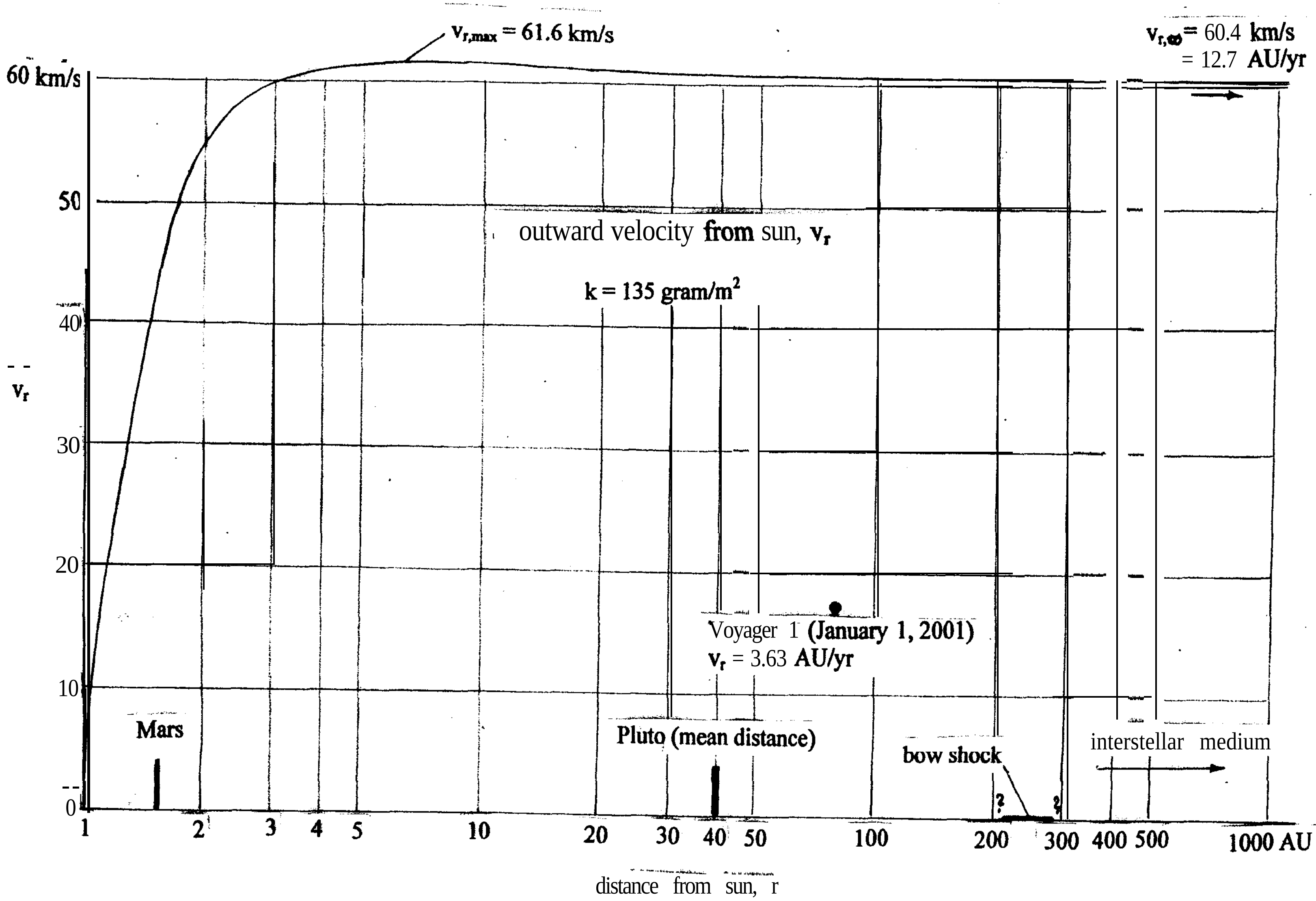
trajectory
$\frac{F(r)}{M(r)}$
$\frac{v^2(r)}{\varrho(r)}$
$\frac{dv}{dt}$
β
$\frac{\mu_h \sin\beta}{r^2}$
$\frac{\mu_h}{r^2}$
$\varrho(r)$
r
sun
center of curvature

		initial	fmal
mass:			
	payload, ion engines, power conditioning, etc.	m_{net} = 100 kg	same
	solar-electric membrane	m_e = 25 kg	same
	propellant (Xenon)	m_x = 500 kg	0
	vehicle, total	M = 625 kg	125 kg
ion engines: $\eta_i = 0.85$			
	beam velocity relative to vehicle	$u_i = 30.10^3$ m/s	same
	specific impulse	I_{sp} = 3060 s	same
	accelerating potential	V_i = 620 V	same
	current (total, all engines)	I_i = 69 A	0
	mass flow rate (total, all engines)	m = 95 mgram/s	0
	thrust (total, all engines)	F = 2.80 N	0
solar-electric membrane:			
	output power	P_e = 50 kW	0
	area:		
	gallium arsenide, $\eta_e = 0.20$	$A_e = 184\ m^2$	same
	amorphous Si, $\eta_e = 0.02$	$A_e = 1840\ m^2$	same
	mass per unit area:		
	gallium arsenide	135 $gram/m^2$	same
	amorphous Si	13.5 $gram/m^2$	same
acceleration:	max.= $0.64\ 10^{-3}\ g_0$	$0.49\ 10^{-3}$ go	0
velocity:			
	heliocentric velocity of vehicle	v = 29.8 km/s	60.4 km/s
	radial component	$v_r = 0$	60.4 km/s

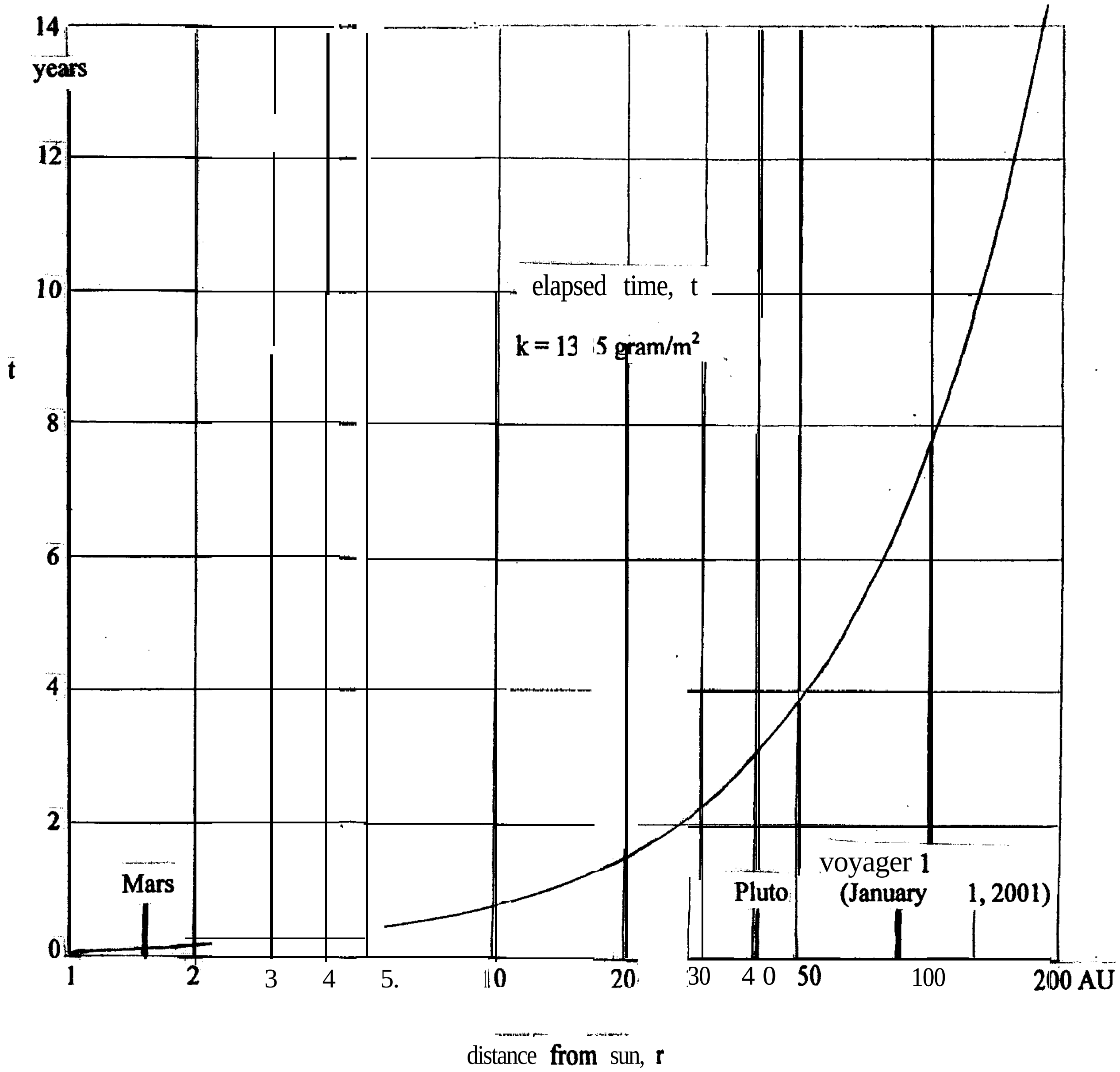
	mass-to-surface ratio
Hubble Space Telescope solar array (Si on kapton sheets, at the blanket level, omitting all structural supports)	905 gram/m^2
Proposed Space Power Satellite (NASA) (omitting structural supports)	200
kapton, 7.6 μm thick (smallest thickness commercially available)	8.4
aluminum conductor at 20 ^{0}C, (calculated for a solar array with $I_{e,max}$ = 81 A, voltage drop = 0.01 V_e)	0 . 3
postulated in this paper:	
kapton supported mono-crystalline film	135
kapton supported amorphous film	13.5

Table 1: Comparison of some mass-to-surface ratios

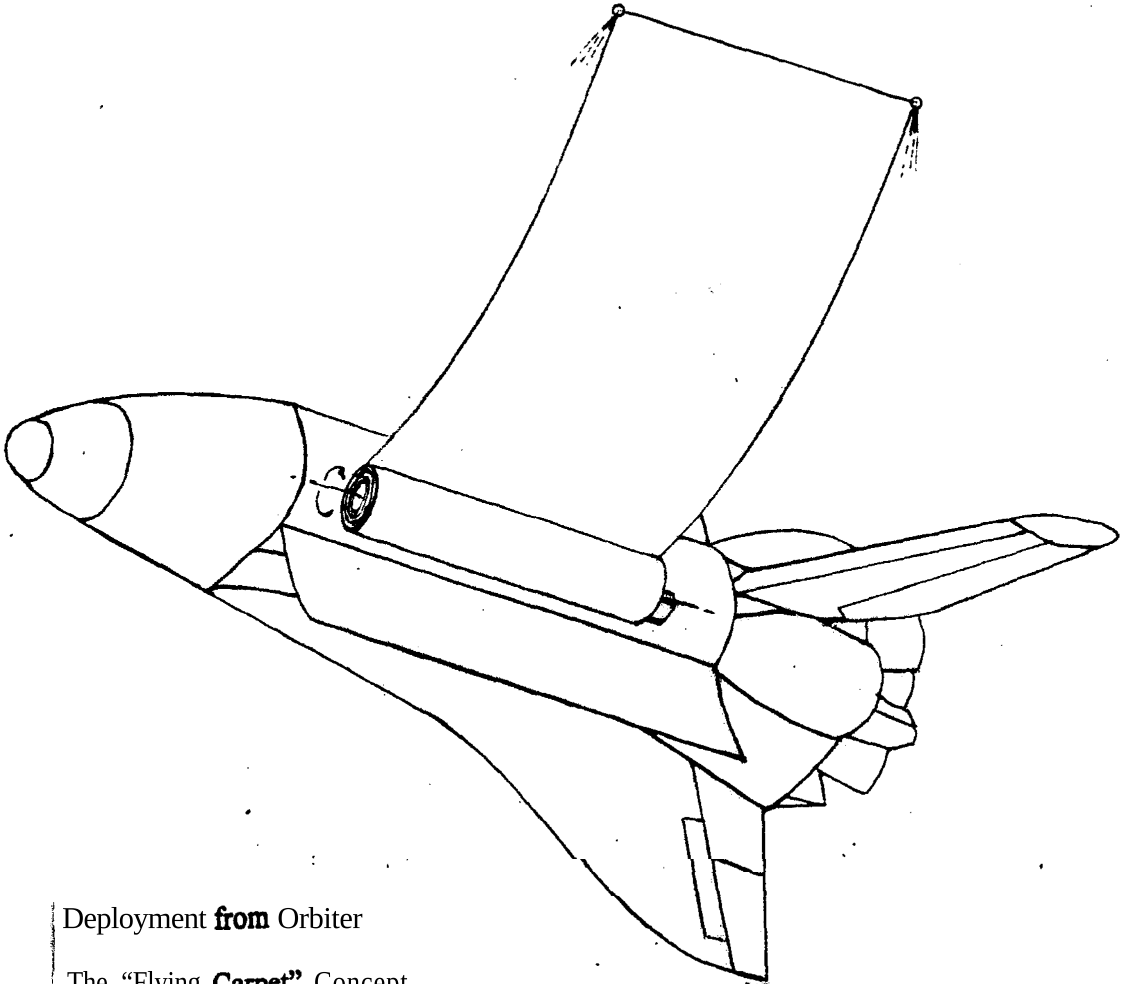

At r = ∞: v = 60.4 km/s
67.3
68.2
63.1
57.2
Earth Orbit
49.5
41.2
35.0
r_0 = 1 AU
v = 29.8 km/s
Sun



$v_{r,max}$ = 61.6 km/s
$v_{r,\infty}$ = 60.4 km/s
= 12.7 AU/yr
60 km/s
50
40
30
20
10
0
v_r
outward velocity from sun, v_r
k = 135 gram/m^2
Voyager 1 (January 1, 2001)
v_r = 3.63 AU/yr
Mars
Pluto (mean distance)
bow shock
?
?
interstellar medium
1
2
3
4
5
10
20
30
40
50
100
200
300
400
500
1000 AU
distance from sun, r

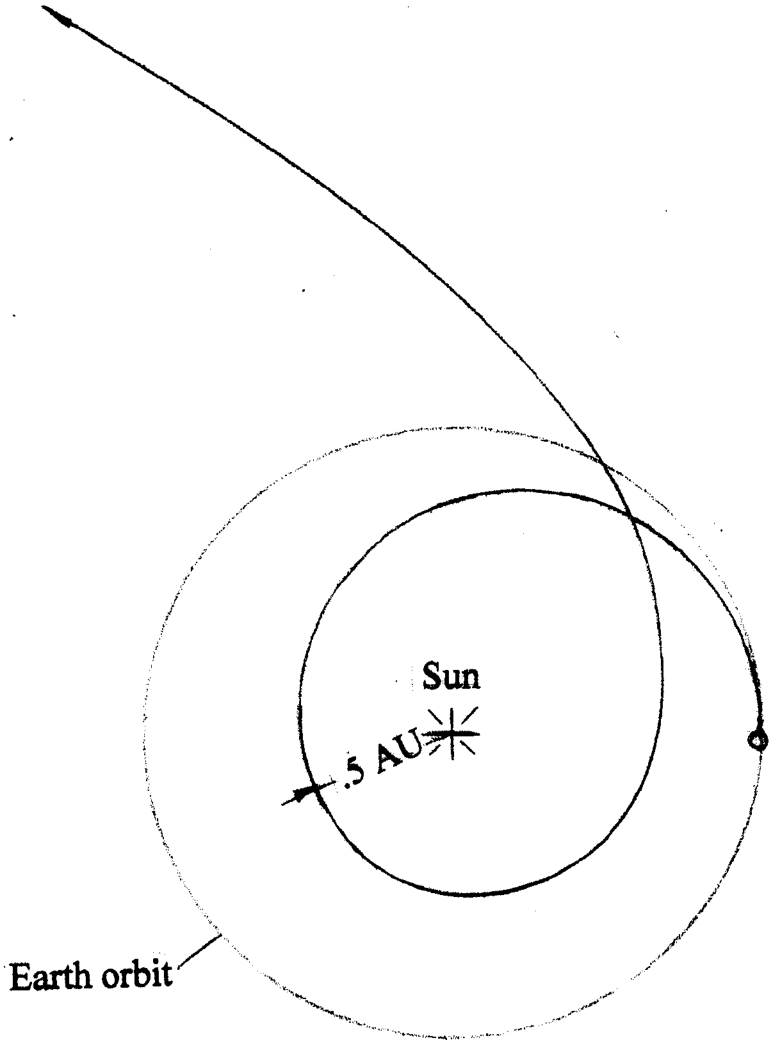


14
years
12
10
8
6
4
2
0
t
elapsed time, t
k = 13 5 gram/m2
Mars
Pluto
voyager 1
(January 1, 2001)
1
2
3
4
5.
10
20
30
4 0
50
100
200 AU
distance from sun, r



Deployment from Orbiter

The "Flying Carpet" Concept



Schematic of a **trajectory** with solar swing-by

Main Technical Challenges

(1) development of large (100 m^2 or more) photo-electric membranes at no more than 150 $gram/m^2$ with gallium arsenide)
or 15 $gram/m^2$ with amorphous Si

(2) tensioning and control of large membranes by electric thrusters.

(3) deployment in space of large membranes.

(4) development of ion engines with variable mass flow.